

The potential of multi-frequency multi-polarized ALOS-2/PALSAR-2 and Sentinel-1 SAR data for aboveground forest biomass estimation

Thota Sivasankar^{#1}, Junaid Mushtaq Lone^{#2}, K.K. Sarma^{#3}, Abdul Qadir^{#4}, P.L.N. Raju^{#5}

[#] North Eastern Space Applications Centre, Department of Space, Umiam-793103, Meghalaya, India

¹ siva.iirs@gmail.com, ² junaidlonez11@gmail.com, ³ sarmakk@gmail.com,

⁴ aqzeeshan78@gmail.com, ⁵ plnraju@gmail.com

Abstract— A reliable assessment of above ground forest biomass spatial distribution is needed for various applications ranging from carbon and bioenergy policies to sustainable forest management. Remotely sensed images have become one of the primary sources for rapidly assessing the above ground biomass (AGB) from local to global scales. Among various remote sensing techniques, Radar remote sensing has shown promising results for forest ecosystem studies due to its unique sensitivity towards dielectric, geometrical and structural properties of vegetation cover. In this study, we have investigated the use of multi-frequency multi-polarized synthetic aperture radar (SAR) data from different sensors i.e., ALOS-2/PALSAR-2 and Sentinel-1/SAR for AGB estimation. Field inventory data from about 53 plots of 1 ha size each, collected from Nongkhylllem wildlife sanctuary and reserve forest located in the state of Meghalaya, India have been utilized for analysis. As anticipated from previous studies, the L-band backscatter has shown higher sensitivity towards AGB than C-band. Moreover, cross polarization has shown higher sensitivity towards AGB than like polarization. An attempt has been made of utilizing the multi-polarized backscatter for AGB retrieval using Support Vector Machine (SVM). An attempt has also been made to train and validate the SVM using C-band VH backscatter and L-band HV backscatter for AGB estimation. This model observed R and RMSE of 0.96 and 21.30 ton/ha respectively. The study results indicate that the multi-frequency cross polarized backscatter can significantly improve the AGB retrieval accuracy than single-band multi-polarized backscatter.

Keyword - multi-frequency, multi-polarized, above ground biomass, SAR, SVM

I. INTRODUCTION

Forests provide variety of ecosystem services which are of great importance to mankind. Forests are an important natural 'break' on climate change because they sequester and store more carbon than any other terrestrial ecosystem (www.fsi.nic.in). Forests play a crucial role in the global carbon cycle and climate change as there occurs about 80% of the plant biomass in forests ecosystems [1]-[3]. Amount of carbon dioxide that can be removed from the atmosphere by afforestation or reforestation can be calculated by biomass density estimates. To understand response to climate change and to estimate carbon pools, the accurate estimation of forest biomass is imperative [4]-[6]. Forest biomass includes both aboveground biomass (AGB) and belowground biomass. Among several available methods for AGB estimation, field based measurements are more accurate but this method is not feasible for large area monitoring due to its labour intensive and time consuming nature. Remote sensing has become an important tool for estimating and monitoring forest biomass over large areas. There are different types of data, such as optical, radar and LiDAR, with each one having certain advantages over the others.

The ability of Synthetic Aperture Radar (SAR) to penetrate vegetation canopy up to a certain depth, its all weather capability and sensitivity to vegetation structure and water content have made it a promising and widely used technique for AGB estimation. Backscatter values and Interferometry technique are used for biomass estimation, of which regression technique based on backscattering amplitudes is commonly used in AGB estimation [7]-[10]. The wavelength (X, C, L, P), polarization (HH, VV, HV, VH), incidence angle, land cover, and terrain properties (e.g. roughness and dielectric constant) are important factors influencing the backscattering coefficient of land cover surfaces [11], [12]. In a tropical forest, AGB estimation can be limited to the lower saturation level at as low as 30 ton ha⁻¹ at C-band, 50 ton ha⁻¹ at L-band and 150-200 ton ha⁻¹ at P-band [13]. SAR backscatter has a reasonable relationship with the forest stand parameters e.g., DBH, Height, basal area, age, timber volume, biomass and carbon stock [14], [15]. In rugged or mountainous regions, topographic factors such as slope and aspect can considerably affect vegetation reflectance, resulting in spurious relationships between AGB and backscattering values. Complex terrain leads to varying backscatter mechanisms which can modify relationship between AGB and SAR backscatter, thus terrain variables need to

be incorporated into AGB estimation studies using SAR data [16]. Sun et al. [17] found that multi-polarization L-band SAR data were useful for AGB estimation of forest stands in mountainous areas. The depth of penetration of SAR signal into vegetation canopy depends on frequency of the signal at a particular incidence angle [18]. Longer wavelengths with cross-polarised data yield better results than shorter wavelengths with co-polarised data with respect to vegetation biophysical parameters retrieval as the incoming signal gets depolarised during multiple scattering inside the vegetation volume [18]-[20]. Saturation which is a limitation of using SAR data depends on polarizations, wavelength, vegetation and ground characteristics [9], [14], [16]. However, saturation problem can be reduced by taking ratio of polarisation and/or wavelengths which also increases correlation between AGB and backscatter [21].

Previous studies have also made an attempt for AGB estimation using multi-frequency backscatter. Enghart et al., [22] has observed that the multi-temporal L- and X-band backscatter combined model can significantly improve the accuracy than using single frequency. Several researchers have also analysed the integrated use of SAR and optical datasets for AGB retrieval. For example, Deng et al., [23] has estimated AGB by combining ALOS PALSAR and WorldView-2 data. Laurin et al., [24] investigated the performance of AGB estimation by using SAR multi-frequency data as well as joint SAR and optical data. It was observed that the both models provide similar accuracy. However, AGB estimates based on multi-frequency SAR data were more conservative than those based on joint SAR and optical data. Because of the complex relationship of microwave frequencies backscatter with vegetation components properties, it is still a challenging task to retrieve AGB.

In this study, we investigated the potential of multi-frequency multi-polarized (L-band HH, HV and C-band VV, VH) Advanced Land Observing Satellite/Phased array L-band synthetic aperture radar (ALOS-2 / PALSAR-2) and Sentinel-1 C-band SAR data for above ground forest biomass estimation over Nongkhylllem Reserve Forest and Wildlife Sanctuary, Meghalaya, India. The integration of PALSAR-2 and widely available Sentinel-1 SAR data and their respective polarizations were investigated in order to develop a model to improve AGB estimation. Support Vector Machine (SVM) technique was used to retrieve AGB using L- band multi-polarized and C-band multi-polarized data. SVM model parameters such as penalty coefficient C (indicates the trade-off between the tolerated training error and the model complexity), ϵ -insensitive loss and kernel parameter γ were optimised for each case on trial and error basis. SVR calculates the difference between the estimated and the actual values, the regression function is considered to be most desirable and accurate if the error is less than the ϵ (tolerated training error i.e., ϵ -insensitive loss) [25]. Several previous studies have observed better accuracies with SVM and Random Forest than other machine learning methods like Neural Network [26].

II. MATERIALS AND METHODS

A. Study Area

The study area covers “Nongkhylllem Wildlife Sanctuary and Reserve Forest” situated in the state of Meghalaya, India (Fig.1). The Nongkhylllem area has a tropical monsoon climate with temperature between 6°C to 32°C. The annual rainfall ranges between 2000-3000 mm in the region. Slope ranges from 0 to 49.85 deg. and the elevation varies from 200 to 950 meters in the study area. Complex terrain causes change in backscattering mechanism and terrain slope induces changes in incidence angle [17], [27]. Thus topographic characteristics should be included to refine AGB retrieval using SAR data in hilly areas. Keeping this in consideration field data and subsequent backscatter signature was taken from terrain slope less than 15 deg. of the study area. The important tree species are *Schima wallichii* (8.26%), *Shorea robusta* (5.37%), *Tectona grandis* (4.82%), *Sterculia villosa* (4.36%), *Castanopsis spp.* (4.11%), *Bauhenia spp.* (4.00%), *Tetramales nudiflora* (3.85%), *Artocarpus loocha* (3.70%), *Albizzia procera* (3.53%), *Michelia champaca* (3.46%), *Callicarpa arborea* (3.42%) and *Miscellaneous spp.* (51.12%) (Forest and Environment Department, Govt. of Meghalaya).

B. Datasets and Processing

In this study, The European Space Agency (ESA) Sentinel-1 C-band SAR data was acquired in interferometric wide swath mode on 15 November 2014 with 5×20 m (Range \times Azimuth) spatial resolution, incidence angle between 30.76 to 46.27 deg and polarisation of VH and VV along with the Japan Aerospace Exploration Agency (JAXA) L-band ALOS-2/PALSAR-2 acquired in fine beam mode on 14 November 2014 with 9.1×5.3 m (Range \times Azimuth) spatial resolution, incidence angle between 36.2 to 42.53 deg. and polarisation of HH and HV.

The field data acquired from Meghalaya Forest and Environment Department contains diameter at breast height (dbh) from 53 plots of 1 ha. The tree volume derived from species specific volumetric equations was converted into dry biomass by using species wise specific gravity as the product of specific gravity and volume (m^3) [28], [29]. The sampled plot size and sample size are sufficient for target parameter retrieval from fine beam mode ALOS-2 PALSAR-2 data as well as interferometric wide swath mode Sentinel-1 SAR data [30].

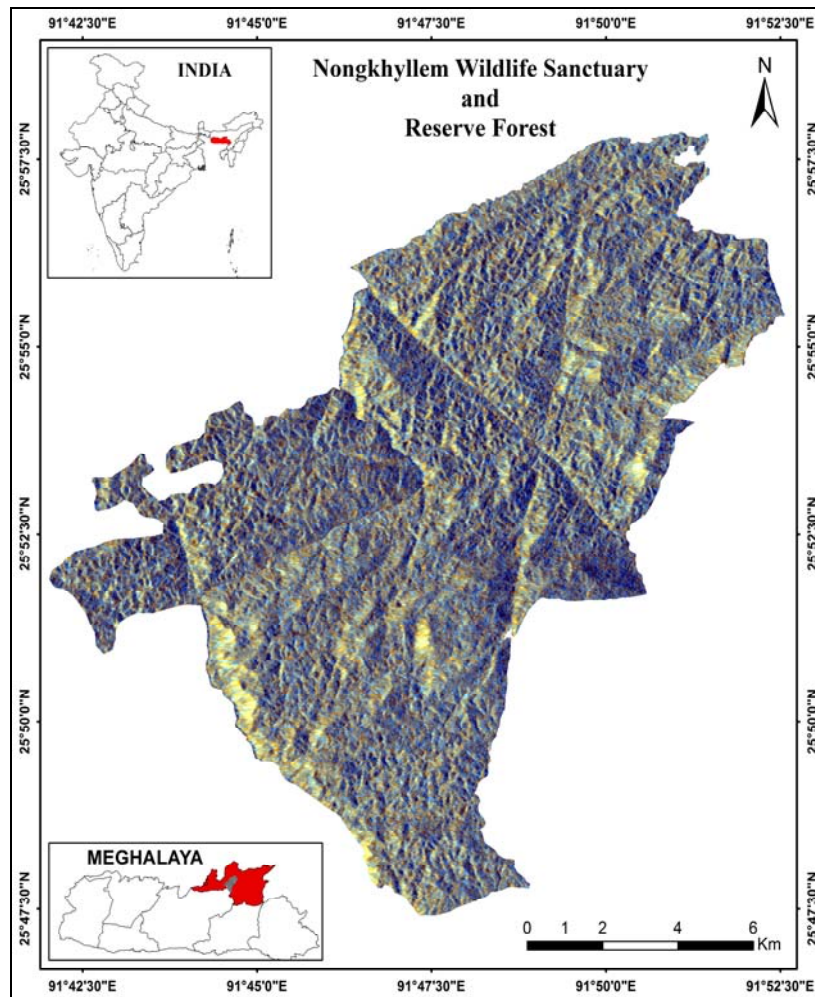


Fig. 1. Study area of Nongkhylllem wildlife sanctuary and reserve forest, Meghalaya, India.

SAR datasets from both Sentinel-1 and PALSAR-2 were calibrated using Sentinel Application Platform (SNAP) toolbox provided by ESA to generate backscattering coefficients and were resampled to 10 m pixel spacing. Refined Lee filter was applied for speckle noise reduction. Terrain correction in mountainous region is necessary to compensate for influence of ground topography on backscattering coefficients [27]. Range Doppler Terrain Correction method available in SNAP toolbox using SRTM DEM of 1sec was employed for terrain corrections. Backscatter coefficient (σ^0 , in dB) values for each ground truth location were extracted from both the scenes of PALSAR-2 and Sentinel-1. The extracted backscatter signatures of C-band VH, VV polarisations and L-band HV, HH polarisations were correlated with AGB individually. Also SVM technique was used to obtain the relation between AGB and SAR backscatter from single frequency multi-polarization i.e., VV and VH (C-band), HH and HV (L-band) along with HV and VH of L-band and C-band respectively.

III. RESULTS AND DISCUSSION

A. Regression Analysis

The total 53 sampled plots used in this study were divided into two independent sets with sample size of 42 and 11 for model development and validation respectively. Regression analysis was performed between AGB and backscattering coefficients of L-band HH and HV polarizations as well as C-band VV and VH polarizations separately. As anticipated from previous studies, the analysis observed that the logarithmic relationship is best fitted for backscattering coefficients with AGB as given in Equation (1) [22], [31]. The scatter plots of backscattering coefficients and in-situ AGB for L-band and C-band are given in Fig. 2 and Fig. 3 respectively.

$$\sigma^0 \text{ (dB)} = a \ln(\text{AGB}) + b \quad (1)$$

Where σ^0 (dB) = backscattering coefficient in decibel; AGB = aboveground biomass in ton/ha and a, b = coefficients.

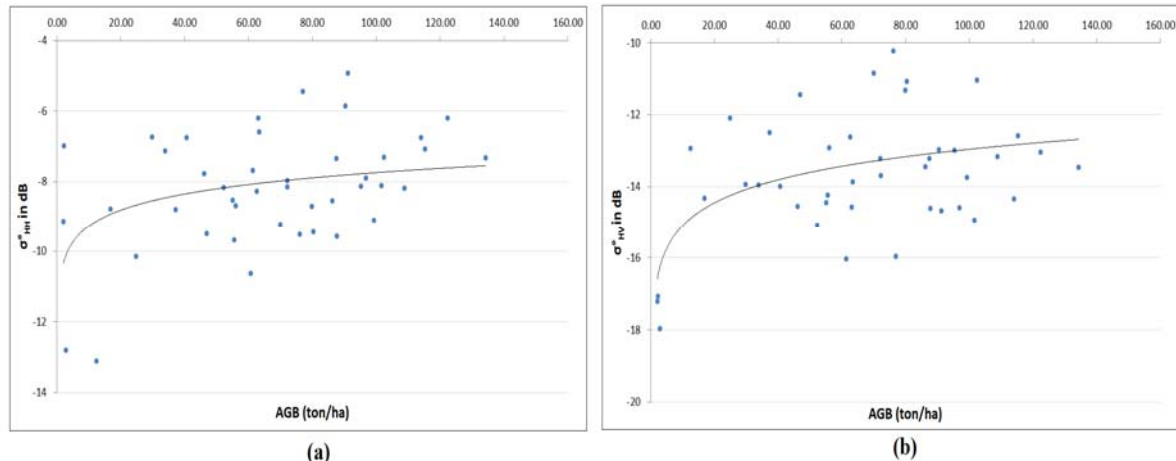


Fig. 2. Scatter plots of L-band HH and HV backscatter with AGB

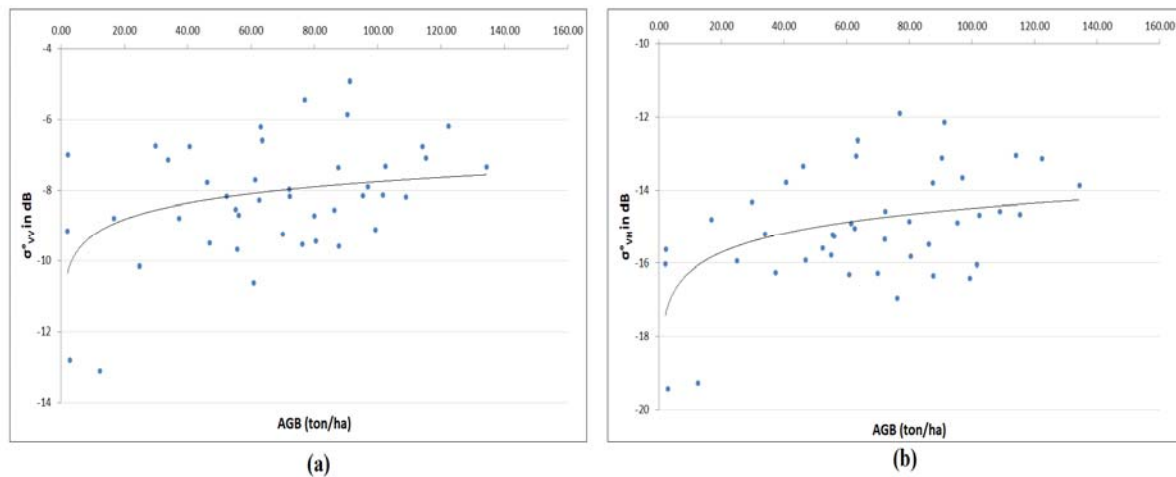


Fig. 3. Scatter plots of C-band VV and VH backscatter with AGB

The results obtained reveal that ALOS-2/PALSAR-2 backscatter is more sensitive than Sentinel-1 SAR backscatter due to the higher saturation levels of longer wavelengths. The regression analysis observed the 'R' value of 0.33 and 0.48 for L-band HH and HV backscatter respectively; whereas 0.3 and 0.35 for C-band VV and VH backscatter respectively. It is also observed that increase in 'R' and decrease in RMSE using cross polarization than co-polarisation of 0.15 and 8.51 ton/ha respectively for L-band; whereas 0.05 and 5.98 ton/ha respectively for C-band. This confirms that the cross polarisation is more suitable for vegetation biophysical parameters retrieval than co-polarisation [18], [19].

B. Multi-polarized single frequency models

The analysis was further continued by training and validating the SVM using multi-polarized SAR data for both L-band and C-band. Previous studies have observed that the use of multi-polarized SAR data can significantly improve the vegetation biophysical parameters [31] and soil moisture [32] retrieval accuracy. In this study SVM, a machine learning technique, has been trained and validated for AGB retrieval. By properly examining the correlation and error, the SVM model parameters C , ϵ and γ (radial bias function kernel parameter) have been set to optimal values for each case separately. The results observed 'R' and RMSE of 0.89 and 33.51 ton/ha respectively for C-band; whereas the 0.92 and 25.8 ton/ha respectively for L-band. It was identified that the multi-polarized SAR data can improve the forest AGB estimation than single polarized SAR data. It is also observed that the multi-polarized L-band data can provide better AGB retrieval accuracy than multi-polarized C-band data.

C. Multi-frequency cross-polarized model

In the next step, an attempt was also made to train and validate SVM using multi-frequency cross-polarized SAR data for AGB retrieval. This study results depict that the 'R' and RMSE of 0.96 and 21.3 ton/ha respectively. It is also observed that the use of combined L-band and C-band cross polarized SAR data can improve AGB retrieval accuracy by increasing 'R' and decreasing RMSE of 0.04 and 4.5 ton/ha respectively

than multi-polarized L-band; whereas 0.07 and 12.21 ton/ha respectively than multi-polarized C-band. This indicates that the combined use of L- and C-band cross polarization backscatter can compensate the errors of L-band at lower biomass areas and errors of C-band at higher biomass areas. The detailed study results for model development and validation are given in Table 1. These analyses suggest multi-frequency cross polarized SAR data for forest AGB retrieval accuracy than single frequency multi-polarized SAR data.

Table 1. Results of the model development and validation of regression analysis as well as SVM based models

Method	Backscatter used	Model Development		Model Validation	
		R	#	RMSE (ton/ha)	#
Regression Analysis	L-band HH	0.33	42	55.23	11
	L-band HV	0.48	42	46.72	11
	C-band VV	0.3	42	59.09	11
	C-band VH	0.35	42	53.11	11
SVM based models	L-band HH and HV	0.92	42	25.8	11
	C-band VV and VH	0.89	42	33.51	11
	L-band HV and C-band VH	0.96	42	21.3	11

represents the number of samples.

IV. CONCLUSION

This research was aimed to assess the potential of multi-frequency multi-polarized SAR data for AGB retrieval. In this paper, the L-band and C-band ALOS-2/PALSAR-2 and Sentinel-1 SAR datasets have been used. The in-situ AGB sampled locations from terrain slope less than 15 deg. have been considered for better understanding the multi-frequency multi-polarized SAR data for AGB in the absence of terrain characteristics (degree of slope and aspect) influence.

As anticipated from previous studies, the L-band and cross polarization backscatter have shown higher sensitivity towards AGB than C-band and co-polarization. In this study, we have observed the correlation between L-band HH and AGB as well as HV backscatter and AGB with 'R' of 0.33 and 0.48 respectively. Whereas the C-band VV and VH backscatter have shown sensitivity towards AGB with 'R' of 0.30 and 0.35 respectively. An attempt has been made of utilizing the multi-polarized backscatter for AGB retrieval using Support Vector Machine (SVM). The SVM based model using C-band VV and VH backscatter observed 'R' and RMSE of 0.89 and 33.51 ton/ha respectively. Whereas, the SVM based model using L-band HH and HV backscatter observed 'R' and RMSE of 0.92 and 25.80 ton/ha respectively. This indicates that the use of multi-polarization backscatter can significantly increase AGB retrieval accuracy rather than using single polarized SAR data. An attempt was also made to train and validate the SVM using C-band VH backscatter and L-band HV backscatter for AGB estimation. This model observed R and RMSE of 0.96 and 21.30 ton/ha respectively. The study results indicate that the multi-frequency cross polarized backscatter can significantly improve the AGB retrieval accuracy than single-band multi-polarized backscatter.

However this study has shown the importance of multi-frequency cross polarization SAR data for AGB estimation, the SVM model is developed and validated in the absence of terrain effects. There is a need in developing a more robust and precise AGB retrieval model in particular for North East India, where terrain is highly undulated. So, this work can be further continued with more number of sample data by considering terrain characteristics along with multi-frequency cross polarized SAR data.

ACKNOWLEDGMENT

The authors are highly thankful to Japan Aerospace Exploration Agency (JAXA) for provision of ALOS-2 PALSAR-2 data and European Space Agency (ESA) for provision of Sentinel-1 SAR data. We acknowledge the support extended by Forest and Environment Department, Govt. of Meghalaya, India in field information sharing.

REFERENCES

- [1] R. A. Houghton, F. Hall, and S. J. Goetz, "Importance of biomass in the global carbon cycle," *Journal of Geophysical Research*, vol. 114, G00E03, 2009. doi: 10.1029/2009JG000935.
- [2] H. Chi, G. Sun, J. Huang, Z. Guo, W. Ni, and A. Fu, "National forest aboveground biomass mapping from ICESat/GLAS data and MODIS imagery in China," *Remote Sensing*, vol. 7, no. 5, pp. 5534-5564, 2015. doi: 10.3390/rs70505534.
- [3] R. K. Deo, M. B. Russell, G. M. Domke, H-E. Anderson, W. B. Cohen, and C. W. Woodall, "Evaluating site-specific and generic spatial models of aboveground forest biomass based on Landsat time-series and LiDAR strip samples in the Eastern USA," *Remote Sensing*, vol. 9, no. 6, pp. 598, 2017. doi: 10.3390/rs9060598.

- [4] T. Le Toan, S. Quegan, M. W. J. Davidson, H. Balzter, P. Paillou, K. Papathanassiou, S. Plummer, F. Rocca, S. Saatchi, H. Shugart, and L. Ulander, "The biomass mission: mapping global forest biomass to better understand the terrestrial carbon cycle," *Remote Sensing of Environment*, vol. 115, no. 11, pp. 2850-2860, 2011. doi: 10.1016/j.rse.2011.03.020.
- [5] A. T. Hudak, E. K. Strand, L. A. Vierling, J. C. Byrne, J. U. H. Eitel, S. Martinuzzi, and M. J. Falkowski, "Quantifying aboveground forest carbon pools and fluxes from repeat LiDAR surveys," *Remote Sensing of Environment*, vol. 123, pp. 25-40, 2012. doi: 10.1016/j.rse.2012.02.023.
- [6] J. M. Barbosa, I. Melendez-Pastor, J. Navarro- Pedreño, and M. D. Bitencourt, "Remotely sensed biomass over steep slopes: an evaluation among successional stands of the Atlantic forest, Brazil," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 88, pp. 91-100, 2014. doi: 10.1016/j.isprsjprs.2013.11.019.
- [7] H. Balzter, C. S. Rowland, and P. Saich, "Forest canopy height and carbon estimation at Monks Wood National Natural Reserve, UK, using dual-wavelength SAR interferometry," *Remote Sensing of Environment*, vol. 108, no. 3, pp. 224-239, 2007. doi: 10.1016/j.rse.2006.11.014.
- [8] H. S. Srivastava, P. Patel, Y. Sharma, and R. R. Navalgund, "Detection and density mapping of forested areas using SAR interferometry technique," *International Journal of Geoinformatics*, vol. 3, no. 2, pp. 1-10, 2007.
- [9] N. Ghasemi, M. R. Sahebi, and A. Mohammadzadeh, "A review on biomass estimation methods using synthetic aperture radar data," *International Journal of Geomatics and Geosciences*, vol. 1, no. 4, pp. 776-788, 2011.
- [10] M. M. Rahman, and J. T. S. Sumantyo, "Retrieval of tropical forest biomass information from ALOS PALSAR data," *Geocarto International*, vol. 28, no. 5, pp. 382-403, 2013. doi: 10.1080/10106049.2012.710652.
- [11] H. S. Srivastava, "Interaction of multi-frequency multi-polarized DLR ESAR data with various targets: A case study with C, L and P bands acquired at all the four linear (VV, HH, VH and HV) polarizations," *JEP-MW Conference*, 15-16 May 2007, Space Applications Centre, Ahmedabad, India..
- [12] H. S. Srivastava, M. L. Manchanda, and S. Adiga, "Use of Radarsat SAR data in forestry (delineation of Acacia forest density)," In *National Symposium on Remote Sensing for Natural Resources with Special Emphasis on Watershed Management, ISRS Symposium* 119-121, 22-24 March 2000, Bhubaneswar, India.
- [13] T. Le Toan, S. Quegan, I. Woodward, M. Lomas, N. Delbart, and G. Picard, "Relating radar remote sensing of biomass to modelling of forest carbon budgets," *Climate Change*, vol. 67, no. 2-3, pp. 379-402, 2004. doi: 10.1007/s10584-004-3155-5.
- [14] N. Joshi, E. T. A. Mitchard, M. Brolly, J. Schumacher, A. Fernández-Landa, V. K. Johannsen, M. Marchamalo, and R. Fensholt, "Understanding 'saturation' of radar signals over forests," *Scientific Reports*, vol. 7, 3505, 2017. doi:10.1038/s41598-017-03469-3.
- [15] G. Sun, W. Ni, F. Hall, J. Masek, T. Fatoyinbo, and D. Peddle, "Retrieval of forest biophysical parameters using physical-based algorithms," *2013 IEEE International Geoscience and Remote Sensing Symposium – IGARSS*, Melbourne, VIC, 2013, pp. 2621-2624. doi: 10.1109/IGARSS.2013.6723360.
- [16] J. M. Lone, T. Sivasankar, K. K. Sarma, A. Qadir, and P. L. N. Raju, "Influence of slope aspect on above ground biomass estimation using ALOS-2 data," *International Journal of Science and Research*, vol. 6, no. 6, pp. 1422-1428, 2017. doi: 10.21275/ART20174506.
- [17] G. Sun, K. J. Ranson, and V. I. Kharuk, "Radiometric slope correction for forest biomass estimation from SAR data in the western Sayani mountains, Siberia," *Remote Sensing of Environment*, vol. 79, no. 2-3, pp. 279-287, 2002. doi: 10.1016/S0034-4257(01)00279-6.
- [18] P. Patel, H. S. Srivastava, S. Panigrahy, and J. S. Parihar, "Comparative evaluation of the sensitivity of multi-polarized multi-frequency SAR backscatter to plant density," *International Journal of Remote Sensing*, vol. 27, no. 2, pp. 293-305, 2006. doi: 10.1080/01431160500214050.
- [19] M. C. Dobson, F. T. Ulaby, T. Le Toan, A. Beaudoin, E. S. Kasischke, and N. Christensen, "Dependence of radar backscatter on coniferous forest biomass," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, no. 2, pp. 412-415, 1992. doi: 10.1109/36.134090.
- [20] T. Le Toan, A. Beaudoin, J. Riou, and D. Guyon, "Relating forest biomass to SAR data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, no. 2, pp. 403-411, 1992. doi: 10.1109/36.134089.
- [21] K. J. Ranson, and G. Sun, "Mapping biomass of a northern forest using multifrequency SAR data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 32, no. 2, pp. 388-396, 1994. doi: 10.1109/36.295053.
- [22] S. Englhart, V. Keuck, and F. Siegert, "Aboveground biomass retrieval in tropical forests – the potential of combined X- and L-band SAR data use," *Remote Sensing of Environment*, vol. 115, no. 5, pp. 1260-1271, 2011. doi: 10.1016/j.rse.2011.01.008.
- [23] S. Deng, M. Katoh, Q. Guan, N. Yin, and M. Li, "Estimating forest aboveground biomass by combining ALOS PALSAR and WorldView-2 data: a case study at Purple mountain national park, Nanjing, China," *Remote Sensing*, vol. 6, pp. 7878-7910, 2014. doi: 10.3390/rs6097878.
- [24] G. V. Laurin, J. Balling, P. Corona, W. Mattioli, D. Papale, N. Puletti, M. Rizzo, J. Truckenbrodt, and M. Urban, "Above-ground biomass prediction by Sentinel-1 multitemporal data in central Italy with integration of ALOS2 and Sentinel-2 data," *Journal of Applied Remote Sensing*, vol. 12, no. 1, 016008, 2018. doi: 10.1117/1.JRS.12.016008.
- [25] A. J. Smola, and B. Schölkopf, "A tutorial on support vector regression," *Statistics and Computing*, vol. 14, pp. 199-222, 2004.
- [26] S. Attarchi, and R. Gloaguen, "Classifying complex mountainous forests with L-band SAR and Landsat data integration: a comparison among different machine learning methods in the Hyrcanian forest," *Remote Sensing*, vol. 6, no. 5, pp. 3624-3647, 2014. doi: 10.3390/rs6053624.
- [27] S. Attarchi, and R. Gloaguen, "A multi-sensor approach for improving biodiversity estimation in the Hyrcanian mountain forest, Iran," *International Journal of Remote Sensing*, 2018. doi: 10.1080/01431161.2018.1468114.
- [28] S. S. Rajput, N. K. Shukla, V. K. Gupta, and J. D. Jain, "Timber mechanics: strength classification and grading of timber," ICFRE publication-38, ICFRE, Dehradun, 103, 1996.
- [29] E. T. A. Mitchard, S. S. Saatchi, L. J. T. White, K. A. Abernethy, K. J. Jeffery, S. L. Lewis, M. Collins, M. A. Lefsky, M. E. Leal, I. H. Woodhouse, and P. Meir, "Mapping tropical forest biomass with radar and spaceborne LiDAR in Lopé National park, Gabon: overcoming problems of high biomass and persistent cloud," *Biogeosciences*, vol. 9, pp. 179-191, 2012. doi: 10.5194/bg-9-179-2012.
- [30] P. Patel, and H. S. Srivastava, "Ground truth planning for synthetic aperture radar (SAR): addressing various challenges using statistical approach," *International Journal of Advancement in Remote Sensing, GIS and Geography*, vol. 1, no. 2, pp. 1-17, 2013.
- [31] P. Patel, and H. S. Srivastava, "RADARSAT-2 announcement of opportunity project on soil moisture, surface roughness and vegetation parameters retrieval using SAR polarimetry," *SAC/EPISA/MPSP/CVD/TDP R&D/01/13*, SOAR International Closing and Reporting – 2013. Final Report Submitted to Canadian Space Agency (CSA) through MDA, Canada, Indian Space Research Organisation (ISRO), India, pp. 1-81, 2013.
- [32] H. S. Srivastava, P. K. Sharma, D. Kumar, T. Sivasankar, R. S. Mishra, M. Mishra, and P. Patel, "Soil moisture variation over parts of Saharanpur and Haridwar districts (India) during November-2006 to June-2007 as observed by multi-polarized (VV/HH & VV/VH) ENVISAT-1 temporal ASAR data," *International Journal of Advanced Engineering Research and Science*, vol. 2, no. 1, pp. 31-39, 2015.